ART WHITING

To Weigh A Man In Space

In March, 1964, Mr. Art Whiting*, a mechanical engineer at the Space Science Laboratory of Colossal Defense Corporation was testing a device he had developed for weighing an astronaut in space. It consisted of a chair with two wheels rolling on a central I-beam plus two outriggers as depicted in Exhibit I. As the chair was rolled forward it stretched a spring. When released, the chair was pulled backward by the spring, accelerating until it reached the limit of travel. From the elapsed time, Art expected to deduce the acceleration, and from the acceleration and spring force he expected to deduce the weight of the chair and its occupant. He had performed a series of tests with men of different weights in the chair and was now ready to compute their weights from the test data to evaluate the effectiveness of his invention. Then he thought he should turn his attention to how the system could be improved in the light of its purpose.

*Names in the case have been disguised.

 Prepared in the Design Division, Department of Mechanical Engineering by Karl H. Vesper with support from the National Science Foundation.

Start of the Project

Art first learned of the desire for something to weigh a man in space when he was called in by his supervisor, Mr. Cal James, and introduced to Mr. Al Lloyd of the Biotechnology Division. Mr. Lloyd explained that he and an electrical engineer had given thought to a system which would consist of a chair suspended from the ceiling on wires which would oscillate back and forth against springs. Then the weight of the passenger would be computed by the frequency of oscillation; a heavy person causing a slower oscillation and vice versa. He said his division wished to use a working prototype as the basis for a proposal to the government for a contract to produce the device and a deadline ten days hence had been set to make the working prototype. Art was assigned by Mr. James to work on the task with Mr. Lloyd as Project Engineer.

Art's background had included studies leading to B.S. (1944) and M.S. (1947) degrees in mechanical engineering at a large midwestern university, plus a masters' in industrial management. He had worked three years for a major home appliance manufacturer on electromechanical controls such as automatic washing machine timers and then for six years as chief mechanical engineer in the tube division of an electronics company. "I left when the company decided to change to a project structured organization rather than staying functionally structured. This meant that most of the mechanical engineers would report to project managers, rather than to me, and my responsibilities were greatly reduced. Besides, in an electronics company, the mechanical engineer is never king on a job. So I was glad to go to work on more mechanical systems here at Colossal." Art had been with Colossal for five years when the project to weigh a man in space arose.

"I suggested we consider hanging the chair by linkage like a garden swing to prevent sideways motion," Art recalled, "but Lloyd said we should reach for something working as soon as possible at the absolute minimum cost. Aside from that we had no given design or performance specifications." The two men considered objectives of minimizing weight and space to be obvious, he said, from the constraints of use in a space capsule, and they soon afterward issued a request for a system to weigh within ½ pound, but Mr. Whiting thought this an unlikely achievement. "The limiting factor is that the human body is not a rigid body. You can vary the reading of a bathroom scale, for instance, just by waving your arms when you stand on it.

"The first question," he continued, "was how to get something working and test results in ten days. To build a machine like this in your garage that fast is easy. But in a big organization you have the additional problem of fighting red tape. To hang the wires from the ceiling meant first I had to have a safety inspector come and certify that it wouldn't weaken the beams or pull the roof down. I had to arrange it with the maintenance people who are in charge of the buildings. Union rules prohibit our own lab technicians from working on the building itself. The machinists have one union, the carpenters have one, and the electricians have another. It's simpler for an electronic engineer. He can walk out to a bench, pick up a soldering iron and make any kind of circuit he wants without checking with anyone."

Art's first action was to make a rough sketch of the proposed system. A chair was to be hung from the 19 foot ceiling by wires. Coil springs first stretched ten inches

each and then attached to the front and rear pulled it back to center if it was displaced. The experimenter was to push it away from center, then release it to allow chair and passenger to oscillate back and forth across center as the springs tried to restore it to the neutral position. To time the period of oscillation Art obtained a stop watch. He wrote requests to the company woodshop to build the chair, to the maintenance department to hang the wires and then visited a local hardware store where he bought some springs. "I didn't know what frequency we should try for," he said, "so I bought two different sizes of springs they had on hand. As it turned out, the weaker springs damped out too fast so we couldn't time more than a few oscillations.

"I did some on the construction work myself," he continued. "I had access to some simple tools, including a drill, a grinder, a band saw, and hand tools. So I bought some parts at the hardware store, and made a few parts like brackets and spring mounts. I figured it was cheaper and it would save time. Besides, in working on the contraption myself I think I got a better feel for the problems of making it work. As it turned out, everything I personally made worked out all right. We had the chair hooked up in just a little over ten working days ready for the first trial (see Exhibit 2).

"We ran it a couple of times to see that it worked and ran calculations with the simple frequency equation $f = \frac{1}{2\pi}\sqrt{\left(\frac{A}{L}\right)^2 \frac{2Kg}{W}}$ to see what results would come out.

The correlation was somewhat off, as I expected, because the equation ignored certain effects, such as friction. I pulled out one of my textbooks from college on vibrations and worked out a more complete equation. It had three terms, one for the spring action, one for the 'pendulum effect' caused by the fact that the chair swung from the ceiling, another for friction. Some of the guys thought there might be a 'hysteresis effect' in the springs, but I didn't think it was significant." The formula then was

$$f = \frac{1}{2\pi} \sqrt{\underbrace{\frac{g}{L}}_{\text{pendulum}} + \underbrace{\left(\frac{A}{L}\right)^2 \frac{2Kg}{W}}_{\text{spring}} - \underbrace{\frac{C^2 g^2}{4W^2}}_{\text{damping}}}$$

where:

g = gravitational constant, 32.2 ft/sec^2
L = distance from point of support to center of gravity (ft)
A = distance from point of support to the springs (ft)
W = weight (lb)
C = damping coefficient (lb-sec/ft)

During experimental runs, Art said, the chair was first displaced not more than nine inches, then released. The stop watch was used to time ten oscillations, which

typically took about 20 seconds. He noticed that when the man in the chair was relaxed his head and shoulder would swing at each end of the stroke and that the result was a changed period of oscillation. He also found that by sitting off center the chair could be made to swing from side to side and again a longer period would result. Consequently, he set a rule that the "passenger" should sit in the center of the chair and as rigidly as he could during all tests. Exhibit 3 shows a plot of test results which Art described in a memo as follows:

> *Results of Initial Experiment* Repeatability within 0.4 sec was obtained over ten cycles. This corresponds to a total variation in apparent subject weight of 3 lb. (i.e. ± 1.5 lb.). Variation of any experimental point from the curve was within ± 4 lb. This range includes the foregoing error.

Acceleration System

"Lloyd didn't think this was accurate enough and so he asked me to prepare a brief written discussion of it as part of a proposal to higher management that we do more work on it. I thought we should consider more alternative schemes at this point and so I did a 'morphological analysis'. I listed alternative ways of determining weight along one side of a page and criteria for performance along another side so we could compare them." (A copy of this page appears as Exhibit 4 along with some of Art's description of alternatives.)

Art explained that he and Mr. Lloyd were generally in agreement on these criteria, except the one concerning "low G force fields." By these, Art meant the force acting when the capsule was in the gravitational pull of a planet or when it was acclerating. In his view these effects might be significant in some missions. Since no particular capsule or mission had been specified for the weighing device he thought they should be assumed. Mr. Lloyd, however, thought they were not important and that the criterion concerned with low force fields should be ignored.

"When Lloyd said the low 'G' force effects should be ignored it made the alternative of measuring by Newton's second law of motion (F = Ma) look best" Art observed, "so we decided to try that as a way of getting higher accuracy. We also decided it would be nice to eliminate the pendulum effect by simply rolling the chair back and forth on wheels."

At this point Art roughed out a sketch of the proposed system and also made a forecast estimate of the cost in materials and labor. Excerpts from his notebook showing these estimates appear in Exhibit 5. "Each of us has to keep track of time spent working on different projects using an authorized charge number," he explained. "To charge time to a given number there must be approval of management in the Biotechnology Section, which was granted on the basis of our estimates."

The new system was to use a "Negator" spring, rather than coil springs. The unique feature of this spring is that its restoring force is not proportional to extension as with coil springs, but rather remains constant. Against this spring the chair was to be pulled from neutral like a slingshot, then released. Acceleration then would be

determined from the time taken to travel a given distance. To stop the chair, Art considered several devices, including elastic ("bungee") cords and automobile shock absorbers. He finally decided to let the chair crumple into corrugated cardboard for the initial experiments.

In choosing the size of the negator spring, Art said he considered the necessity for a limited track length to fit in a space ship. He thought it important to accelerate and decelerate slowly enough to avoid discomforting the passenger. "We ordered several springs," he said, "so we could experiment to see which was most appropriate. We thought we should plan on a force of less than one G and so somewhat arbitrarily picked a range of 1/3 to 1/5 G for our trials.

"We planned to install the spring so it would pull the chair forward. A main advantage of this was that then the chair would serve as a brace to hold the passenger's head and back rigid during acceleration. But then when we started asking what would happen if anything broke we decided to attach the spring to the back of the chair where it couldn't possibly hurt anyone if it let go."

To time the travel during acceleration Art used a microswitch which was triggered by a ramp or cam along the course of travel. When the chair began to move, the switch was closed by the cam. After traveling 31.5 inches along the cam it was again opened. An oscillator and electronic counter were triggered by the microswitch to determine time. Art described his construction of the timing system as follows: "I thought the way to do it would be to hook an oscillator to the switches and let the counter keep track of the number of pulses it emitted between start and stop. So I checked out an oscillator and a counter and tried to hook them up according to the instructions that come with the counter. When I had some trouble and asked an electronics engineer for help, he told me the counter already had an oscillator built into it. My circuit was generally all right, but the extra oscillator wasn't necessary."

Next, some passengers were tried in the chair to test the system. Pulling just the chair and passenger with a fish scale, Art measured the frictional drag to be ten ounces with a 170 pound man, and about five ounces empty. In making this measurement, he observed that the scale readings were very high at the srart of the stroke unless he pulled very slowly and evenly. "We took a series of readings," he said, "then averaged the results. I would guess that the accuracy was within plus or minus half an ounce."

In timing the acceleration test runs Art was somewhat disturbed to notice that the times varied widely depending upon how the man who released the "slingshot" let it go. By pulling his hand off quickly a considerably lower time resulted. So testing was stopped, and a solenoid apartment door latch bought at a local hardware store was installed. This improved consistency of the data, according to Art, and resulted in the times shown in Exhibit 6.

Now Art felt he should compute the weight from the test data and see how well it compared to the conventionally measured body weights of the passengers. He began his calculations by assuming that the force acting had several components as follows:

$$F = f_s - f_B - f_R - f_i$$

where:

f = spring force (12.61 lb)
f_B = drag due to ball bearing friction (lb)
f_R = drag due to rolling friction of wheel on track (lb)
f_i = drag due to inertia of each wheel (lb)

From his measured values of friction he thought that .62 pounds would be a resasonable approximation for $f_B + f_R$.

Todetermine f_i he reasoned as follows: for a wheel that accelerates

$$T = I\alpha$$

where:

T = torque (ft-lb)
I = rotational moment of inertia (lb-ft/sec^2)
α = angular acceleration (rad/sec^2)

then, $T = f_iR$ where R = radius of the wheel (ft.) Also, $I = ½\ mR^2$ where m = mass of the wheel (slugs) and $\alpha = a/R$, where a = linear acceleration. Substituting the last three equations in the preceding one:

$$f_iR = (½\ mR^2)\ (a/R)$$

or

$$f_i = ½\ ma$$

Art weighed the wheels and found them to be 13 lbs, so he approximated f_i at 0.2 $(2s/t^2)$. The total cart weight with no passenger in it he measured to be 58 pounds.

He then felt he was ready to apply Newton's second law using the test data to compute passenger weights. "They should be correct within a couple of pounds," he said. "If they're off more than 2½ lbs I should probably look for ways to make further refinements in the system. If they're off still more, I should probably think through the whole approach again and consider whether some other system should be tried; if so, which one."

EXHIBIT 1 – Chair & Rails

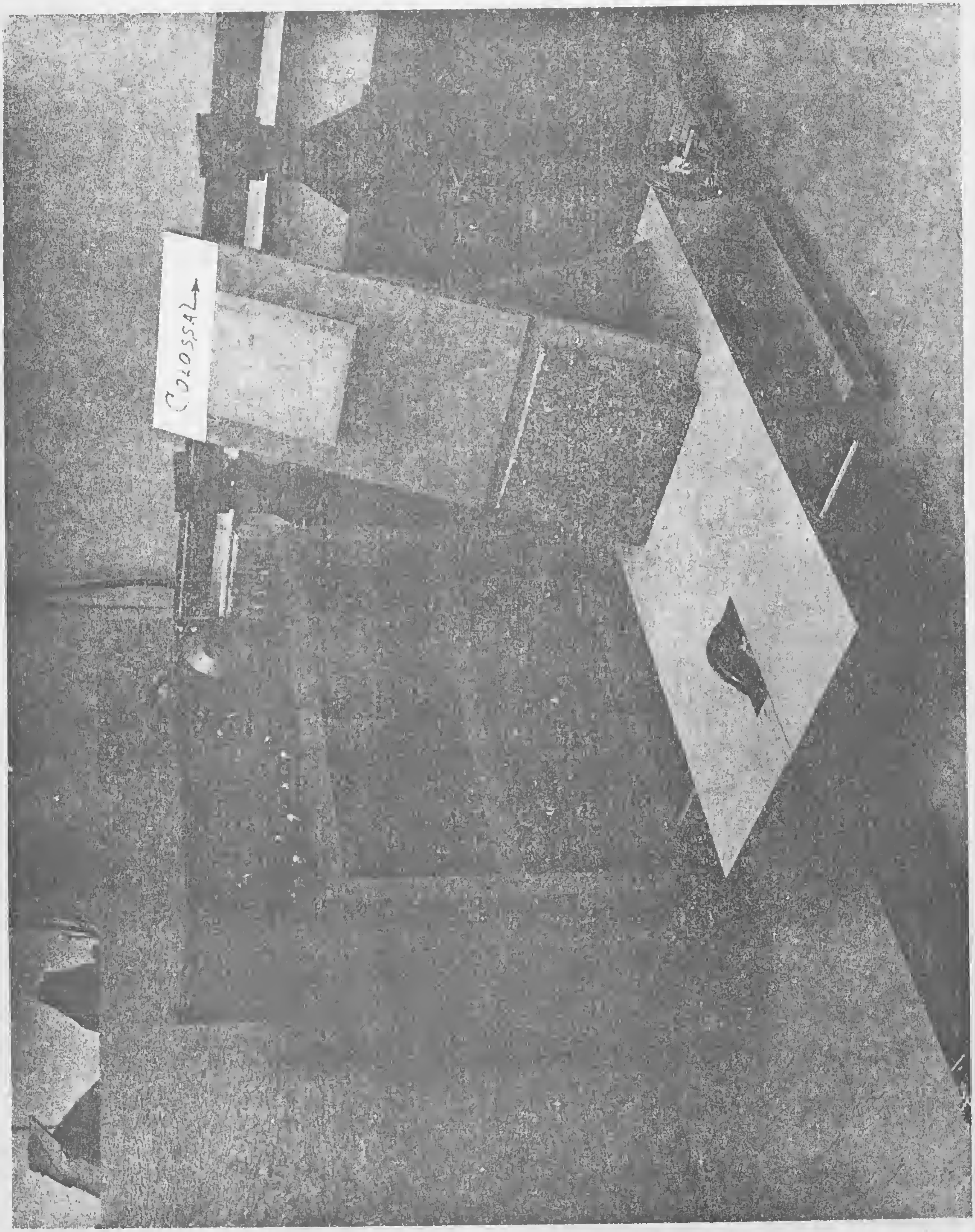
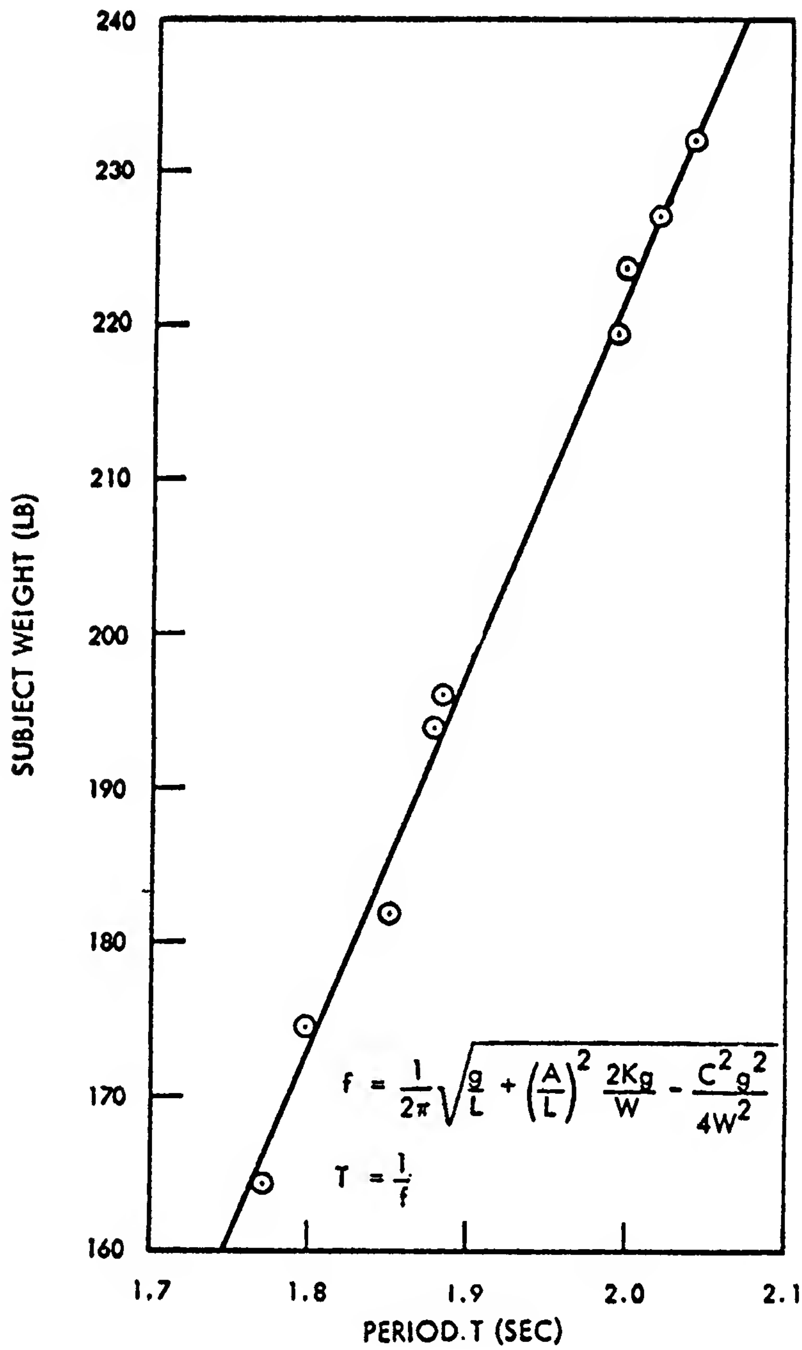


EXHIBIT 2 – Oscillating Mass Measurement System

EXHIBIT 3 - Data From Oscillating System



Relationship Between Body Mass and Period as Determined by Oscillating Spring-Mass Device (Pendulous Support and Stopwatch Timing)

CRITERIA OF COMPARISON FOR ALTERNATE MASS MEASUREMENT SYSTEMS

Effect of Presence of Low Force Fields	Mass Measurement System	Bedding Down	Apparatus Simplicity and Alternatives	Suitability for Ground Evaluation	Effect of Difference in Bearing Friction Between Ground and Orbit	Operational Considerations
Disruptive	Linear acceleration (F = Ma)	Little effect	Electronic timer moderately complex; proposed on-board computer could perform function	Ground evaluation satisfactory; may require recalibration for zero-g condition	Could be appreciable; ground calibration chart requires alteration for orbital use	One shot; a 1 man operation
No effect (unless force field is intermittent for brief periods)	Oscillating Spring-Mass System	Greater adverse effect on accuracy than linear acceleration	Electronic timer moderately complex; proposed on-board computer could perform function; if electronic timer fails, a stopwatch usable (Less accuracy)	Ground evaluation satisfactory; may require recalibration for zero-g condition	Could be appreciable; ground calibration chart requires alteration for orbital use	One shot; a 1 man operation
Effect may be minimized by adding pivot	Intertia-Beam Balance Technique	Phased-stroke solution to potential problem	Simplest system	Ground simulation difficult; elaborate means required	None	Trial and error; possible in 2 man operation
Effect could be compensated	Centrifuge	No Problem	Relatively simple (if centrifuge exists for other purposes)	Ground calibration set-up simulate can zero-g conditition	None	Impose scheduling constraints, unless performed concurrently with other centrifuge function; involves long operating cycle

EXHIBIT 4 MORPHOLOGICAL TABULATION

EXHIBIT 4 –Continued, Description of Alternative Systems

Centrifuge. The equation for centrifugal force is $F = M\omega^2R$ where M is mass, ω, is rotational speed, and R is radius of the path of the mass center. Since R enters this equation linearly, a small error in assumed mass-center location will not be as serious as in the case of the torsional pendulum. However, angular velocity enters quadratically, and will therefore have to be controlled closely. It will not be difficult to measure centrifugal force, but a seat or couch having radial freedom of movement along one arm of the centrifuge will be required.

Impulse Momentum. The equation for this impact action is $F(\Delta T) = M(\Delta V)$. F is a force that is applied over a time period ΔT. M is the mass that is being accelerated from its initial velocity to its final velocity ΔV. In other words, $F(\Delta T)$ represents an impulse which changes momentum $M(\Delta V)$. Both F and ΔT will be difficult to determine because of their transient nature. The presence of random g forces will adversely affect accuracy; therefore, precautions will be required to ensure that no such disruptive forces exist during astronaut mass determination. Further, in a zero-g environment, an astronaut will not be bedded down firmly on the apparatus at the first instant when acceleration starts. Even though he is strapped or clamped in the apparatus, his weightless configuration relative to the inertial forces are present. These considerations make the impulse-momentum method quite impractical.

Conservation of Momentum. The equation for this phenomenon is $MV_1 + mv_1 = MV_2 + mv_2$. It represents a controlled collision in which a smaller known mass (m) traveling with a known initial velocity v_1 strikes the unknown mass M, which is standing still ($V_1 = 0$). A device will be provided to lock the two masses together upon impact so that $V_2 = v_2$. The equation thus becomes $M = (m/v_2)(v_1 - v_2)$. To determine the unknown mass M, the final velocity v_2 must be measured. This can be accomplished by timing the passage of the locked-together masses over a known distance. The disadvantages of this conservation-of-momentum method are that an appreciable auxiliary mass m is needed, and that a considerable jolt will be caused by the impact. Since the presence of random g forces can cause inaccuracies, mass determination should not be attempted unless such forces are absent. The foregoing remarks regarding bedding down apply also to the conservation-of-momentum method and make it impractical.

Linear Acceleration. This method is represented by the equation $F = Ma$ where F is a known, constant force; M is the unknown mass; and a is an acceleration which must be measured. This acceleration can either by measured directly,using an accelerometer, or indirectly by determining the time t to traverse a known distance s; thus, $a = 2s/t^2$. Obviously, time must be measured very accurately since it enters to the second power. If any random g forces are present, they can cause inaccurate results. The bedding down aspect previously noted (the impulse-momentum system) does not apply very strongly to this system ($F = ma$) because it involves a far longer period of acceleration, and the bedding down will take place at the start of motion. Further, the acceleration will be low, and, consequently, the bedding down effect will be smaller in magnitude.

EXHIBIT 4 – Continued, Description of Alternative Systems

Frequency of a Spring-Mass System. The frequency of an oscillating spring-mass system is

$$F = \frac{1}{2\pi} \frac{2K}{M}$$

where

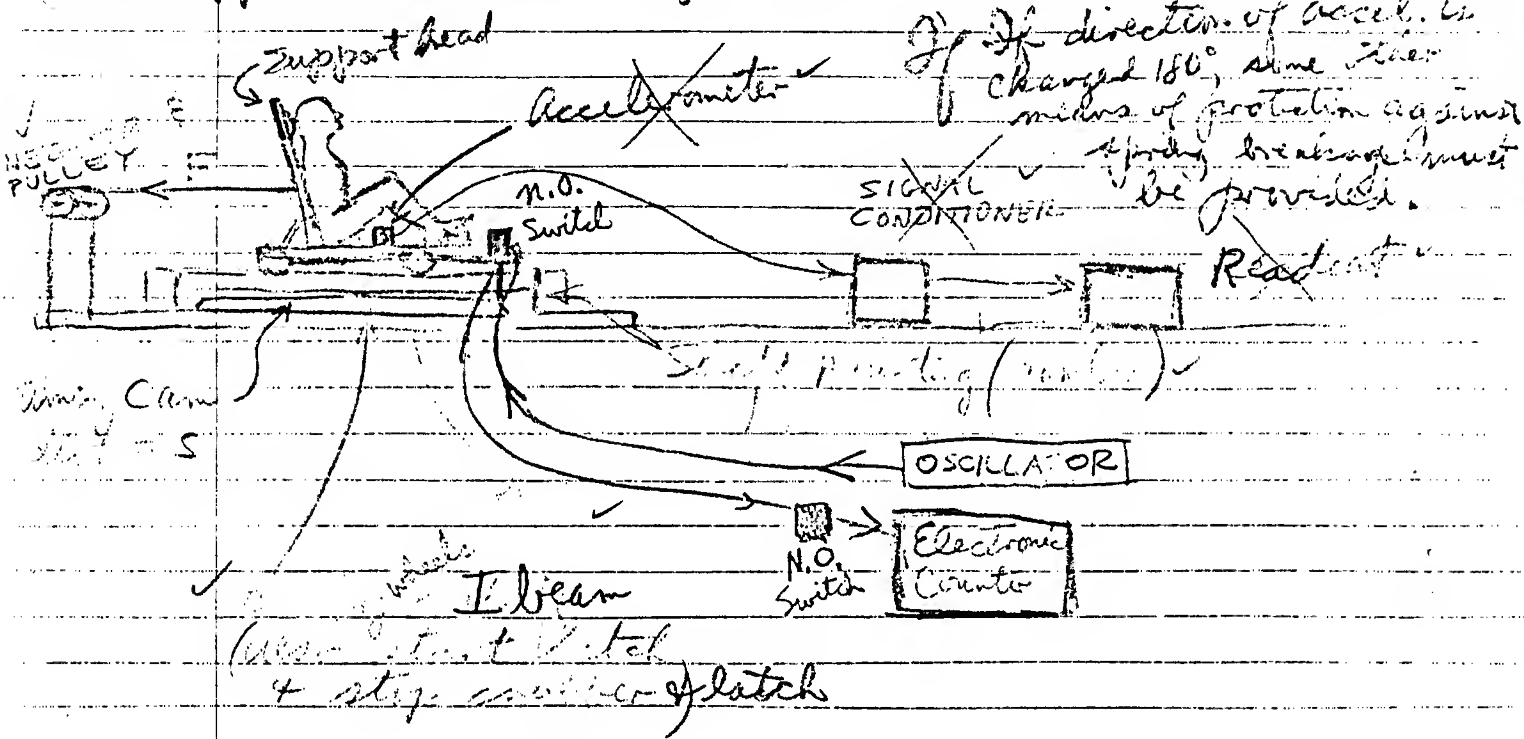
f = frequency (cps)
k = known spring constant
M = unknown mass

One need only provide a single-degree-of-freedom mounting for the unknown mass and a spring system to keep the mass oscillating in simple harmonic motion, and measure the system frequency. Timing can be performed with great accuracy because an average of a large number of cycles can be obtained. Further, the presence of random g forces will have little or no effect on accuracy. With respect to the bedding-down effect, the spring-mass system will probably not be quite as good as the straight linear acceleration system.

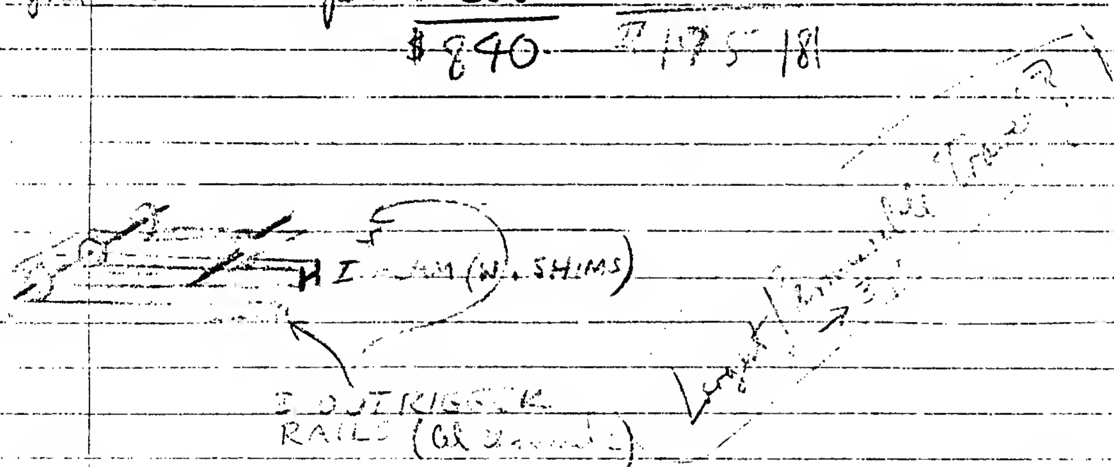
Inertia Beam Balance. A parallel platform-type of beam balance (i.e., a commercial weighing scale) can be employed by applying a momentary acceleration in line with the knife edge so that the resulting inertia force acts to replace gravitational attraction in the weighing function. The momentary acceleration can be obtained by moving the balance upward, using a man-powered lever. This system has the great advantage that no additional instruments of any kind are required since there is no need to measure time, force, acceleration, etc. The presence of a random g force will tend to reduce accuracy slightly, but its existence can be detected by making a trial balance without any subject on the platform. In order to overcome the undesirable effects of the bedding-down problem, a rather long accelerating stroke will be required, perhaps with a provision for performing the balance only during the latter part of the stroke.

Nov. 24, 64 **EXHIBIT 5 - Sketches and Forecasts from Art's Records**

Stripped-down version of F=ma



EST. PURCH. ITEMS	$		
		30	30 Shipping
Negator + Pulley	90	50	50
Linear Ball Brgs + Shaft	175.	[illegible]	76
Accelerometer	350.		—
Switch	25	25	25
Signal Conditioner Components	200	—	
	$840	$175	181



Notes: Wt. + pulley may be used as backup for negator.
TRACK MUST BE LEVELLED.
Negator + pulley } will have inertia
Ball brg. wheels }

aw

EXHIBIT 5 - Sketches and Forecasts, Continued

Nov. 25, '64

Estimate of MAN DAYS to design, build & demonstrate Mass Determination by use of Newton's Second Law of motion (measuring time instead of acceleration).

ENGR. – OTHER

	For Combined Equipment	Switch & Precision Timer	Ball Bearing mounting Start latch & Stop muffler	Negator Spring & Pulley	TOTAL
Prelim. design		1	4	2	7
Detail design		1	6	3	10
Order purch. items		2	3	1	6
Drwgs.		1-2	3-6	1-2	5-10
Mfg. special equip.		2	7	1	10
Set up equip. for test		1-1	2-2	1	4-3
Perform tests	3-2				3-2
Reduce data	2				2
modify equip.			1-1	1-1	2-2
Rerun tests	2-1				2-1
Reduce data	2				2
Write Report	4				4
TOTALS	13-3	6-5	19-16	9-9	47-[illegible]

EST PURCH. ITEMS

Negator & pulley	$50
Shafting	30
Ball Brgs	75
Switches	25
TOTAL	$180

EXHIBIT 6 – Linear Acceleration Test Data (Copied From Mr. Whiting's Notes)

Empty Cart Weight 58.0 Lbs.
Travel 31.5 Inches

Test Number	1	2	3	4
Passenger Weight (pounds)	162½	173½	144¾	271¾
Travel Time (milliseconds)	1764 1745 1759 1745 1765	1816 1795 1802 1810 1806	1686 1688 1678 1681 1679	2144 ~~2165~~* 2122 2116 2113
Average Time (seconds)	1.7556	1.8058	1.6823	2.1238

Test Number	5	6	7	8	9
Passenger Weight (pounds)	201¼	169	161½	186¾	132¾
Travel Time (milliseconds)	1906 ~~1926~~* 1896 1898 1906	1818 1808 1813 1797 1806	1763 1750 1764 1750 1760	1861 1850 1844 1839 1842	1633 ~~1654~~* 1642 1629 1625
Average Time (seconds)	1.90150	1.8084	1.7574	1.8472	1.6323

* Crossed Out on Mr. Whiting's Data Sheet